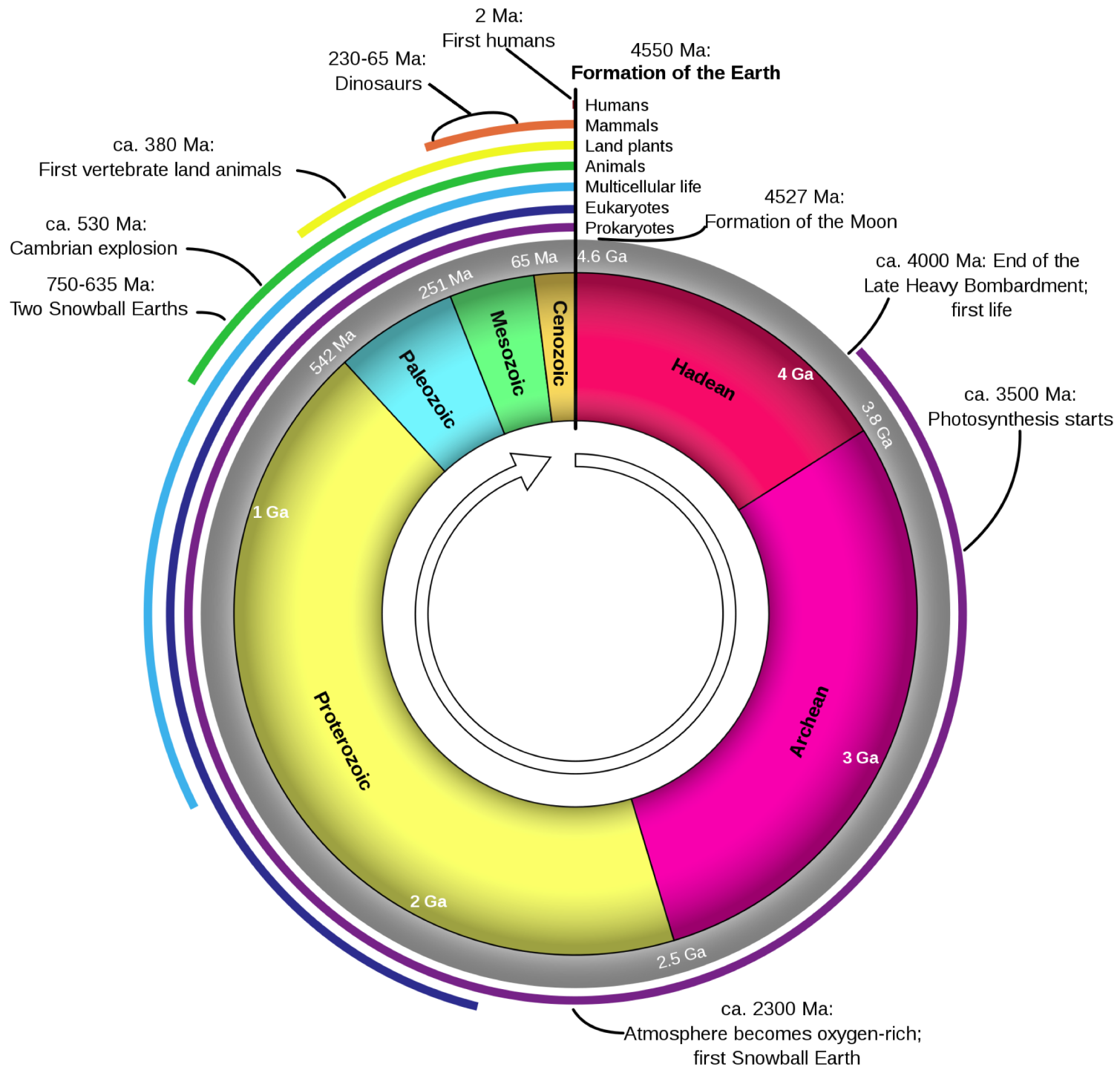


Faint Young Sun Paradox

*Sun was 20-30% less luminous than today
in its early history.*

How did the Earth maintain a warm climate?



Summary

- Sun was 70-80% as luminous as today
 - Maybe CO₂ or CH₄ was more prevalent?
- There is a LOT of evidence that CO₂ concentrations were not much higher back then than today
 - Other arguments for CH₄ as well.
- Mechanism proposed by Sagan & Mullen 1972 (higher NH₃ concentration) was found problematic
- Some early papers proposed cloud feedback as a solution (Rossow et al. 82)
- Lets have a look at the work of the last 2 years that may resolve some of these problems...

Jan 2010 Rondanelli & Lindzen

Can thin cirrus clouds in the tropics provide a solution to the FYSP?

Focus is on tropical cirrus clouds

- Mechanism of formation of cirrus in the tropics appears to be particularly susceptible to a surface temperature dependence (unlike extra-tropical clouds)
- Thin cirrus clouds have a much larger IR heating effect than shortwave cooling and therefore a strong positive cloud radiative effect (Recent satellite estimates confirm this)

Jan 2010 Rondanelli & Lindzen

What about simply using increased CO₂ and CH₄?

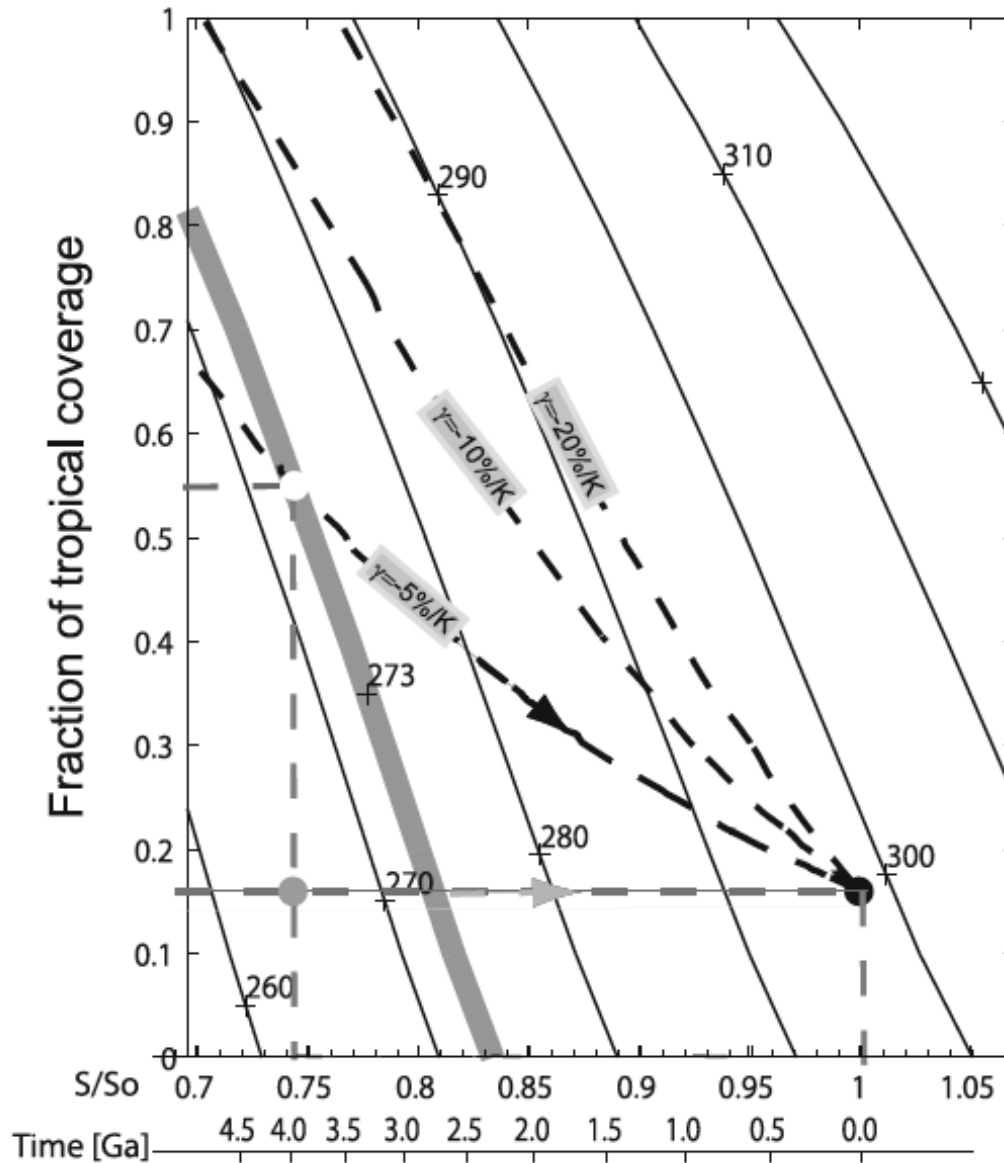
- Several lines of study show that CO₂ could not have been more than 10 times present amount (siderite, etc)
- CH₄ possible, but not when CH₄/CO₂ ratio higher than 1 because of formation of reflective organic haze
 - Contradicted by Wolf & Toon 2010 as well see...

Jan 2010 Rondanelli & Lindzen

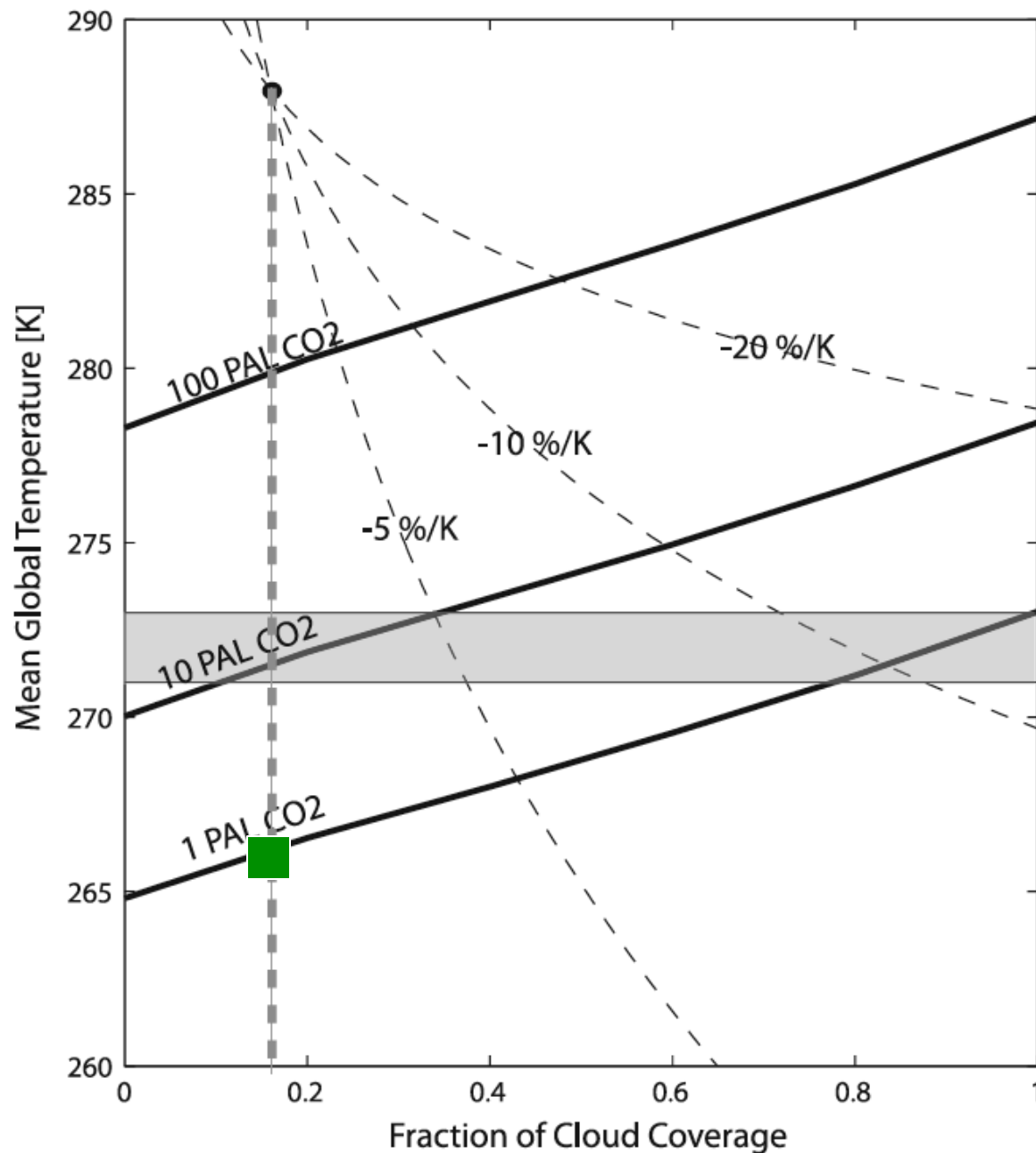
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a. 1-column tropics



black dot → current
white dot → $S=0.74$
 $f \sim 0.55$
grey dot → $S=0.74$
 $f \sim 0.16$



3 different CO2 concentrations for $S=0.8$

current $f \sim 0.16$ (gray dashed line)

green dot is the paradox for $S=0.8$

we need 20 PAL CO2 for $T > 273\text{K}$

hard to solve only with 1 PAL CO2 – need $f \sim 1$!!

Jan 2010 Rondanelli & Lindzen

Go on to check several other things:

- Sensitivity to Cloud Water Content (Fig 3)
 - Have to be just right (not too thin, not too thick)?
- Sensitivity to fixed height assumption (Fig 4)
- Sensitivity to Water Vapor feedback (Fig 5,6)
- Sensitivity to Meridional Heat Flux (Fig 7)

Claim that all of these are minor effects and that their prescription works (Conclusion)

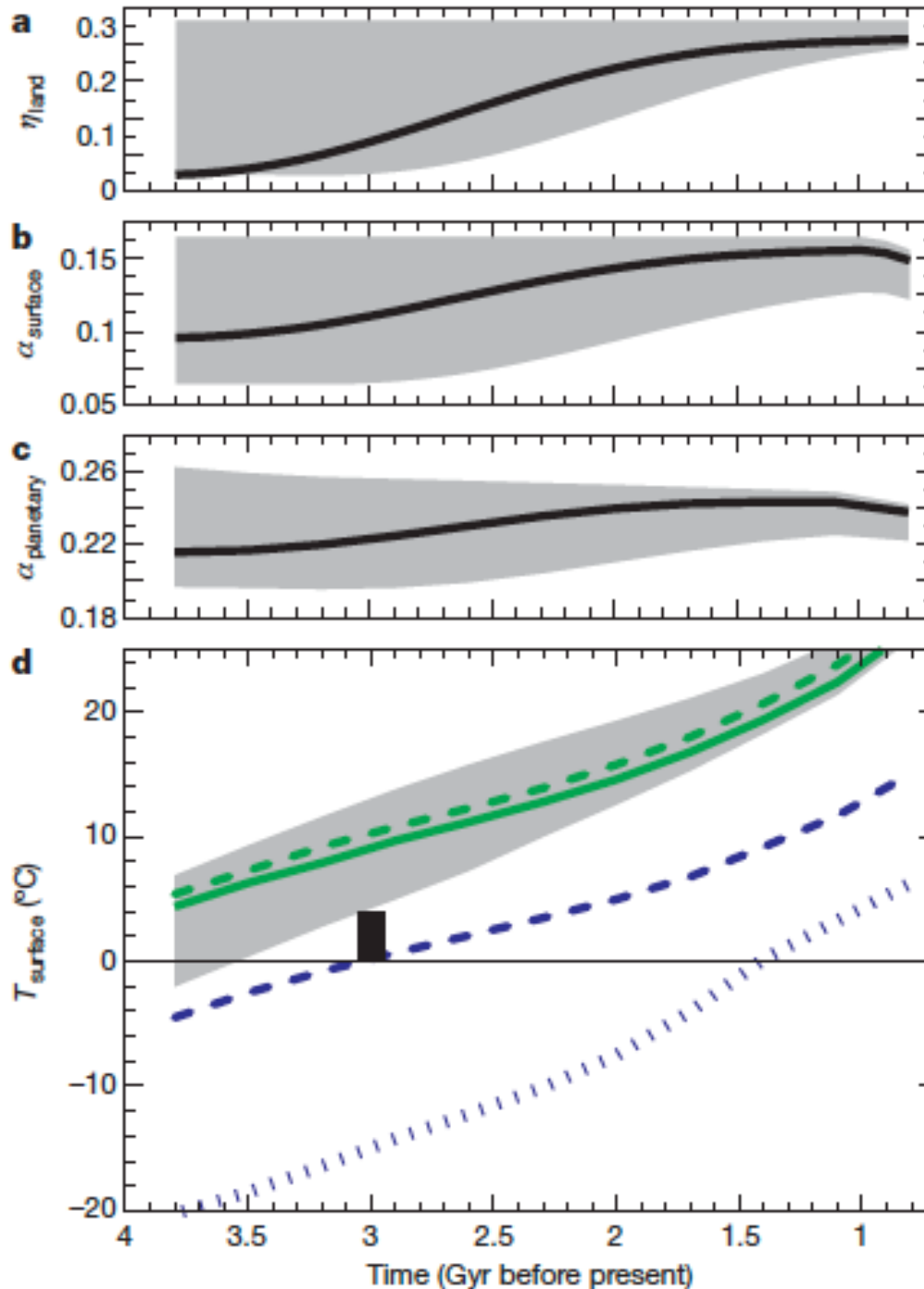
April 2010 Rosing et al.

“No Climate Paradox under the Faint Early Sun”

Lower albedo Earth: less continental area & lack of biologically induced cloud condensation nuclei

- Present lots of evidence for low CO₂ concentrations
- Clouds over early Earth were different:
 - CCN concentrations lower (drop size bigger)
 - Non-oxygenic atm and biosphere devoid of plants and algae
 - Claim the latter is observed over areas with low-productivity gyres in ocean where atm transparency for short wave radiation is higher than areas with high-productivity
 - With more transparent atm, lower albedo ocean more strongly expressed as fraction of total planetary albedo

April 2010 Rosing et al.



Continental fraction of Earth's surface

Surface albedo

Albedo for droplet size of 30um, 900ppmv CO₂ and 900ppmv CH₄

Surface Temp

blue=375ppmv CO₂
1.7ppmv CH₄

- - 20um droplets

|| 12um drops (today)

green=900ppmv CO₂

900ppmv CH₄

— 20um droplets

- - 30um drops (today)

April 2010 Kasting

Faint young sun redux

- Recaps the evidence in Rosing
- Notes at least one problem:
 - ice albedo feedback is ignored
 - Ice caps start to grow with low surface temps and further destabilizes the climate
 - Need 3-D climate models to prove hypotheses, not just 1-D
- Mentions reduced greenhouse gases are favorable:
 - As O₂ concentrations rose CH₄ and other reduced gases decrease rapidly triggering glaciation at end of Archaean.

June 2010 Wolf & Toon

Fractal Organic Hazes Provided an Ultraviolet Shield for Early Earth

Fractal aggregate haze was found to be optically thick in UV while transparent at mid-visible wavelengths

- Archean atmosphere: mostly N₂, CO₂, CH₄, H₂, H₂O
- Dense CO₂ impossible – lack of siderite in fossil weathering profiles
- CO₂+CH₄+**NH₃** combined can work
- Past studies found N₂+CH₄ haze would offset any greenhouse warming from the former

June 2010 Wolf & Toon

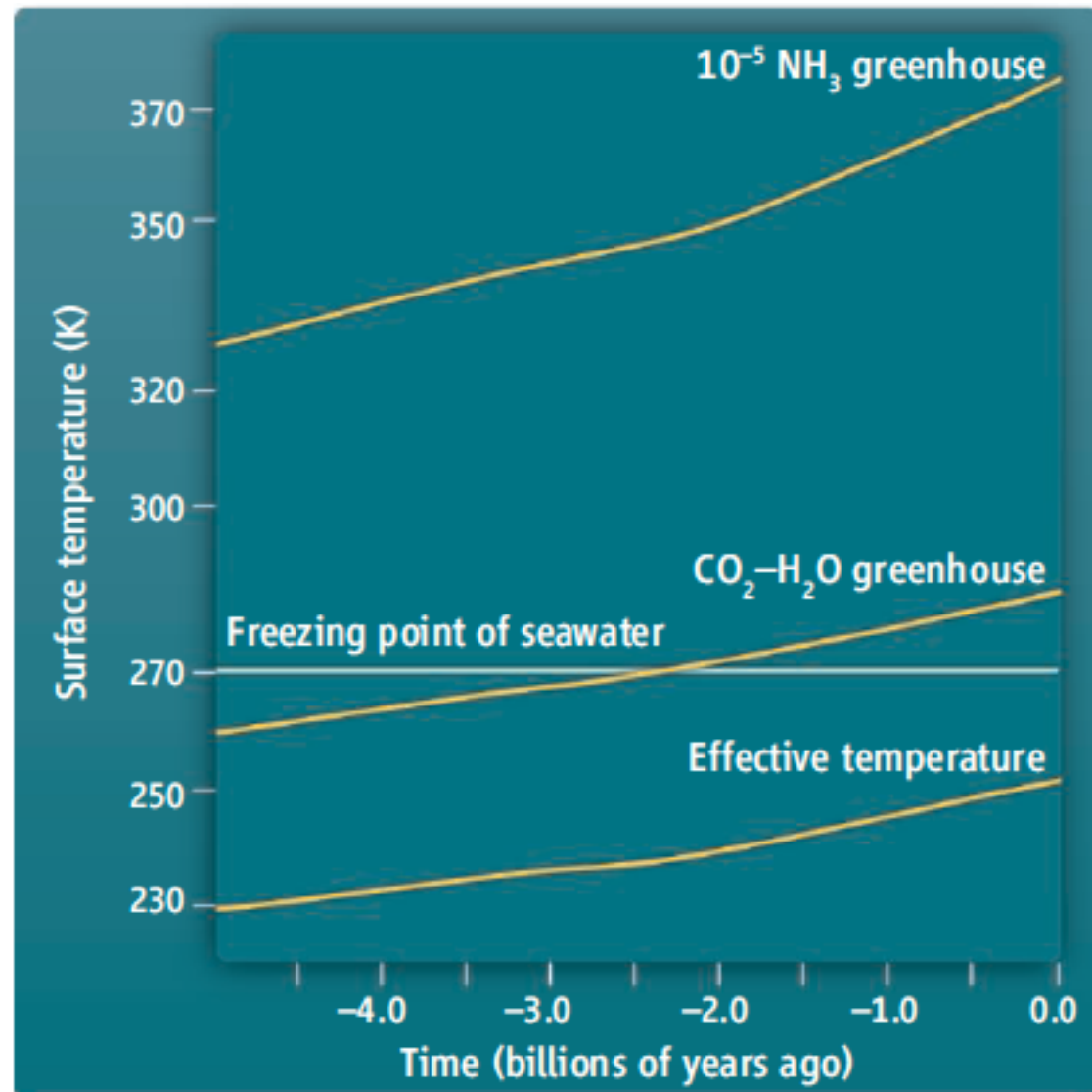
- N₂+CH₄ haze:
 - optically thin in visible & little cooling effect
 - Optically thick in UV (happy plants)
- fractal nature of particles required
 - Previous studies assumed “sphericity”
- hydrocarbon aerosols exhibit fractal structure
 - Affect microphysical and radiative properties of haze
- Modeling haze particles as fractal aggregates:
 - reproduces scattering properties of Titan’s haze
- UV SHIELD PROTECTS NH₃ from disassociation
 - Otherwise converts to N₂ in less than 10 years?
 - Assumes ALL NH₃ below UV shield

June 2010 Chyba

Fractal Organic Hazes Provided an Ultraviolet Shield for Early Earth Letter in support of Wolf & Toon

- Sagan & Mullen first advocated NH_3 , but Kuhn & Atreya later showed that UV radiation would make it into N_2
- Sagan was working on paper to make haze from $\text{N}_2 + \text{CH}_4$ which would allow visible light, but not UV, but it was later found this would absorb too much visible light
- Mentions thicker CO_2 as *still* a possible solution, but given the Rondanelli/Lindzen paper I don't know how??
- He likes the fractal haze, but points out problem with making sure it absorbs all of the UV before hitting the NH_3

June 2010 Chyba



November 2010 Letters

Problems with the formation of life in Wolf/Toon model

- Evolutionary roots of biochemistry draw on CO₂ and H₂ as main nutrients of life
- Meaning that large amounts of CO₂ and H₂ are required, not less?

Feb 2010 Goldblatt & Zahnle

Clouds and the Faint Young Sun Paradox

- Use 3 layered randomly overlapping clouds to get proper energy budget while “being consistent with observed cloud climatologies” TODAY.
- Decreasing surface albedo can contribute no more than $+5\text{W/m}^2$
- Clouds absorption is largely independent of wavelength in contrast to gaseous absorbers (vib-rot line of molecules)

Feb 2010 Goldblatt & Zahnle

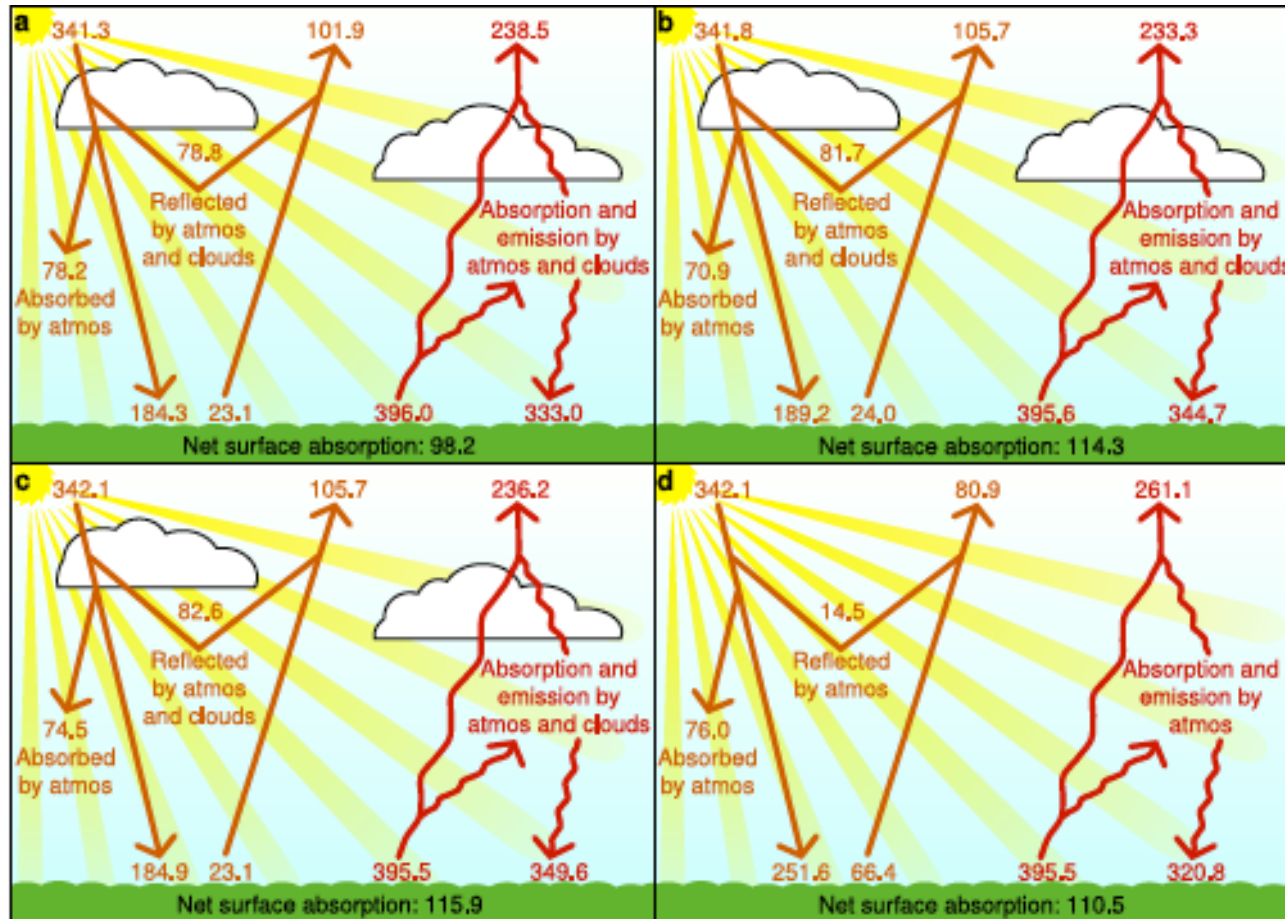
- Rondanelli & Lindzen 2010
 - Their “thin cirrus” have twice water path of this paper
 - Attempt to model “thin cirrus” with 3.5x thicker clouds, whole sky coverage, and raising height of clouds to get to 50.7W/m^2
 - They do not think the latter is realistic
- Rosing et al. 2010
 - Decrease low-cloud albedo (thinner clouds, larger particles 20-30 μm)
 - Decrease liquid water path by 3.7 (arbitrary – why?)
 - Simply not enough forcing available (see Fig 12 of this paper)

Feb 2010 Goldblatt & Zahnle

- Assess changes to radiative properties of clouds w.r.t. FYSP
 - Consider a range of cloud properties w/in a single global mean atm column
 - This should match the Earth's energy budget for a given amt of greenhouse gases
 - Compare this to a cloud-free situation
- Change fraction, thickness, height, and particle size to see how they influence climate (explore a large phase space)
- Water vapor windows would permit significant surface radiation to escape, but clouds and greenhouse gases keep it in
 - Cloud-free model would have to increase gas abundance to get enough absorption

- Use single column radiative-convective models
 - Run millions of these rather than a full climate model (explore parameter space)
 - Fig 5c & d for comparisons of Cloud and no-cloud models for net radiative forcings
 - Very good agreement with observational climatology (Fig 5a & b)
 - “omitting clouds means that global energy budget is not properly represented”

Shortwave Longwave Shortwave Longwave



“real” cloud model Trenberth et al

Cloud free model Zhang et al

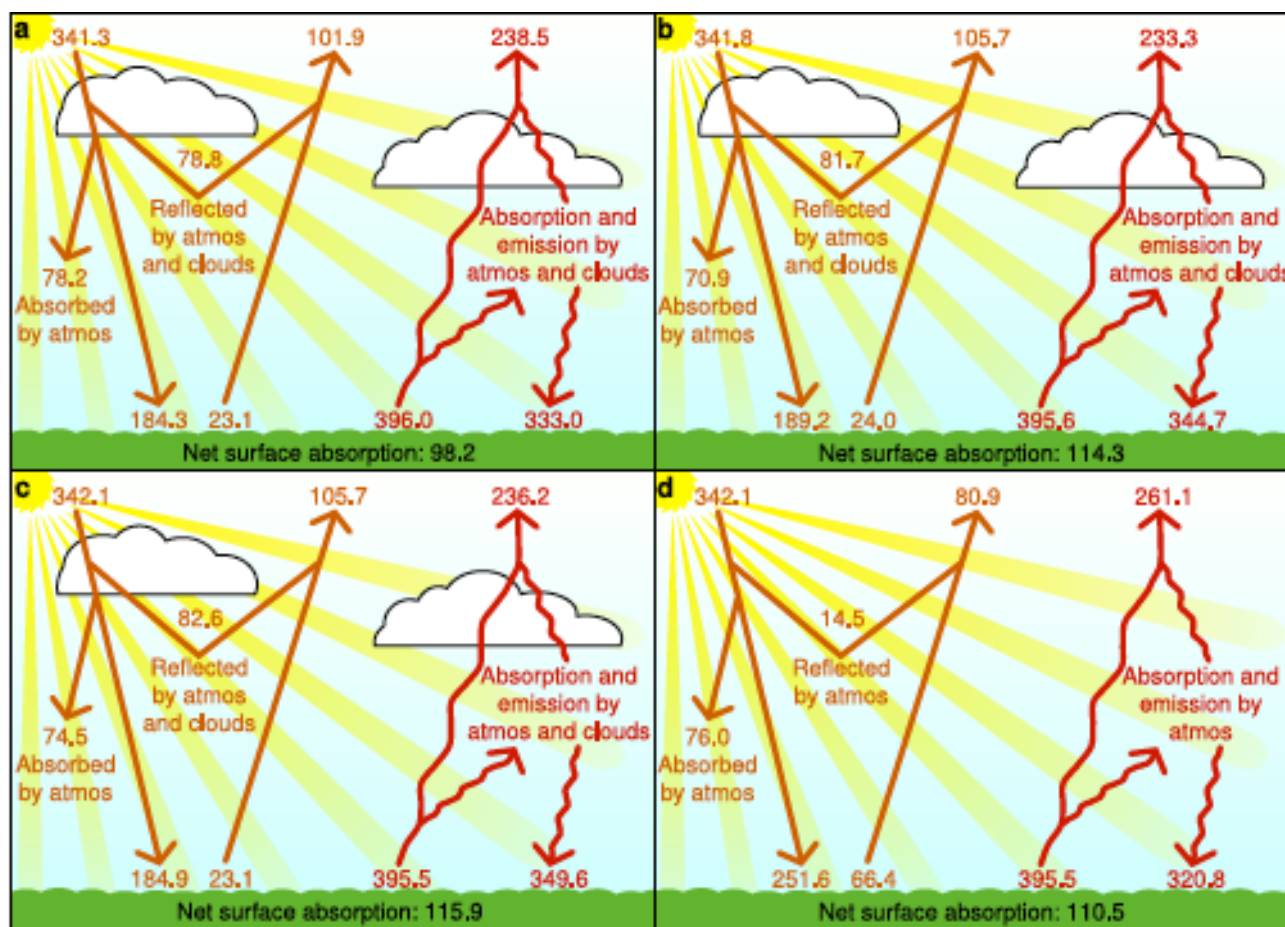
Following Kasting 1984
Surface albedo=0.264

cloud-free model:

more absorption of solar radiation balanced by weaker greenhouse effect

- 81 vs 106 of outgoing shortwave radiation is reflected (lower albedo)
- Elevated outgoing longwave flux of 261 vs 236
- Depressing downward longwave flux at surface (320 vs 350)

Shortwave Longwave Shortwave Longwave



“real” cloud model Trenberth et al

Cloud free model Zhang et al

Following Kasting 1984

Surface albedo=0.264

Feb 2010 Goldblatt & Zahnle

- Fig 6: compares spectrally resolved energy budgets between cloud-free (CF) and real-cloud (RC) models in short-wave and long-wave
 - Large differences in greenhouse effect and solar absorption
- Fig 7: Radiative forcing with increasing CO₂
 - Radiative forcing is strongly overestimated by cloud-free model relative to real-cloud case
- Fig 8: Comparison of spectrally resolved longwave forcings for increasing CO₂ from present to 50,000 ppmv in RC & CF cases.

- Cloud Fraction, water path, particle size, cloud height...
 - More clouds found over southern oceans
 - Less continent area in Archaean, hence more clouds?
 - Water path effects on short & long-wave radiation depend on cloud height
 - Particle size depends on available CCN (Cloud Condensation Nuclei)
 - Larger CCN over ocean (12.5 μ m) than land (8.5 μ m)
 - What made up the CCN now versus then is strongly debated?
 - Possibly different CCN concentrations in Archaean
 - Fewer CCN => larger cloud drops, rain out quicker and less reflective
 - More CCN => more drops, smaller, more reflective
- Cloud height
 - Larger forcing from raising clouds that are thicker or cover more of sky initially
 - Greater the radiative longwave effect at standard height, greater effect of changing its height.
- Pressure of Archean atm was likely not 1 bar -- no oxygen and nitrogen inventory was different? This would change the lapse rate and tropopause pressure, hence the types of clouds?